A HEAVY WATER CERENKOV DETECTOR TO STUDY ^8B SOLAR NEUTRINOS*

presented† for

The Sudbury Neutrino Observatory (SNO) Collaboration

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Abstract

The construction of an observatory using 1000 tons of heavy water in a Cerenkov detector to study ^8B solar neutrinos is proposed. This detector would be used to directly measure the ^8B electron neutrino flux, spectrum, and direction, and the total ^8B neutrino flux, irrespectively of neutrino flavor. It would also have a sensitivity to the spectrum and direction of any ^8B originated electron neutrinos which may have oscillated into muon or tau neutrinos. The characteristics of the heavy water Cerenkov detector and its capabilities are given. The status of the project is only very briefly provided here.

Introduction

The standard solar model predicts that the sun is a steady source of electron neutrinos with a well defined spectrum. The electron neutrinos are produced in the fusion furnace deep inside the sun.[1] The Cl/Ar radiochemical experiment in the Homestake mine by R. Davis et al. has, over the past 15 years, observed an argon production rate by these neutrinos which is at least a factor of three lower than predicted.[2] The strong disagreement between the predictions of the standard solar model and the results of the carefully executed Cl/Ar radiochemical experiment is known as the solar neutrino problem.

The Cl/Ar experiment is primarily sensitive to neutrinos of relatively "high" energy from ^8B decay. The ^8B neutrino intensity is critically dependent on conditions, particularly the temperature, within the solar core. So, a large variety of non-standard solar models have been proposed to lower the temperature in the solar core to resolve the solar neutrino problem.[3] However, these models introduce difficult new astrophysical problems and have not been generally accepted. Alternative solutions of the solar neutrino problem assume that the standard solar model is correct but that the neutrinos have evolved in their flight from the solar core to the earth. Recently, the early suggestion of vacuum neutrino oscillations[4] developed a new direction with the realization by Mikheyev and Smirnov[5] and others[6,7] that the vacuum oscillation effect can be greatly enhanced by neutrino propagation through solar matter. The basic idea underlying this possibility was suggested by Wolfenstein a few years ago.[8] Detailed calculations of how matter oscillations can affect the solar electron neutrino flux and spectrum shape has been discussed by Rosen and Gelb.[7]

The Sudbury Neutrino Observatory (SNO) Collaboration proposes[9] to construct a ^8B solar neutrino observatory located deep underground using 1000 tons of heavy water in a Cerenkov detector in order[10] to study ^8B solar neutrinos and to search for the solution to the solar neutrino problem.

The SNO Heavy Water Cerenkov Detector

The SNO detector design follows those of the IMB collaboration in the United States[11] and the Kamioka group in Japan[12] to search for proton decay but with greater coverage of the detector surfaces by photocathodes for improved sensitivity to Cerenkov light from low energy electrons. The D_2O will be borrowed from Atomic Energy of Canada, Limited (AECL).

A conceptual design of the SNO detector is shown in Fig. 1. The 99.85% pure D_2O will be contained in an acrylic tank with dimensions 10.5 m diameter by 10.5 m high. The acrylic tank will be surrounded by 3.25 m of very clean H_2O and 1 m of low background concrete. Twenty-four hundred 20" diameter Hamamatsu phototubes (PMTs), mounted uniformly in the H_2O 2.5 m from the acrylic tank, will provide 40% coverage of the detector surface by photocathodes. Thus, the sensitive volume of this detector will be constructed of very low radioactivity materials, and the D_2O will be well shielded from external radioactivity.

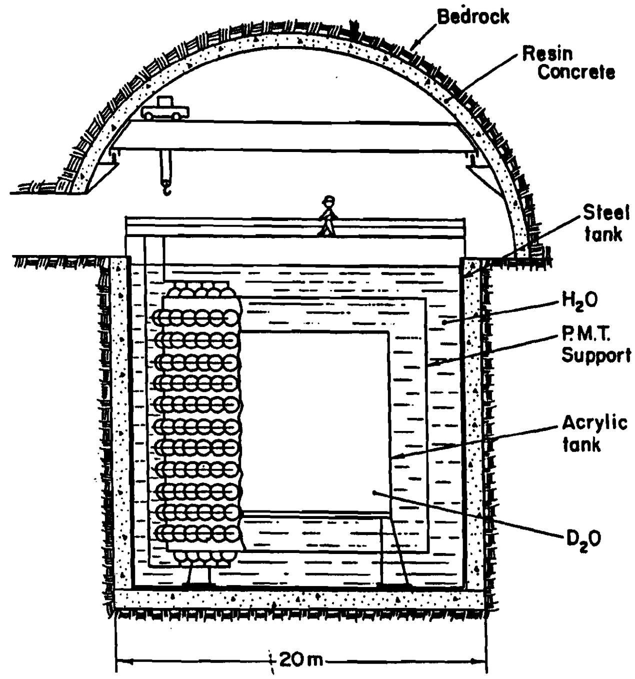

Fig. 1 Conceptual Design of SNO Detector

The detector would be located 2073 m underground in the nickel mine at Creighton operated by the International Nickel Corporation (INCO) near Sudbury, Canada, and the cavity would be located in the non ore-bearing Norite rock. Fig. 2 shows a vertical section of the Creighton mine, and Fig. 3 shows the schematic of the 6800 feet (2073 m) level. Properties of the SNO detector are summarized in Table 1.

^8B Neutrino Detection Capabilities

The SNO detector would be used to directly measure the ^8B electron neutrino flux, spectrum, and

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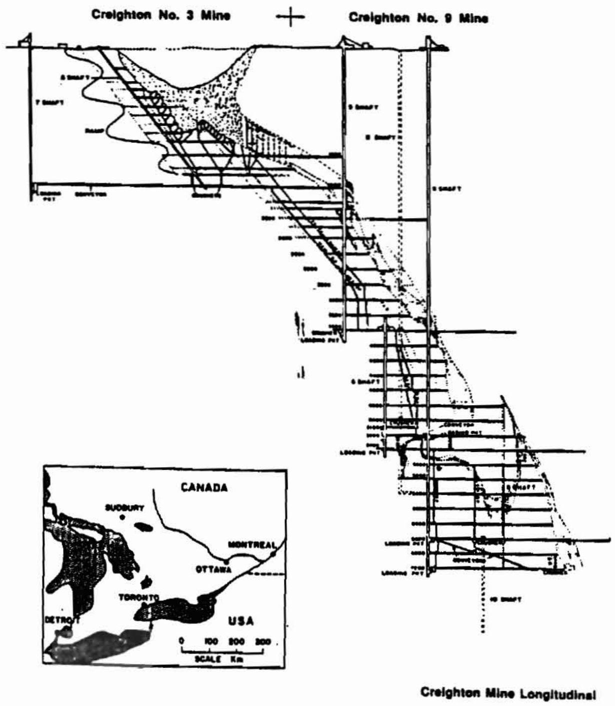

Fig. 2 Vertical Section of Creighton Mine No. 9

direction, and the total ^8B neutrino flux, irrespectively of neutrino flavor. It would also have a sensitivity to the spectrum and direction of any ^8B originated electron neutrinos which may have oscillated into muon or tau neutrinos.

The unique capabilities of the SNO detector come from using the following three neutrino reactions:

			Q value
(1)	$\nu_e\ d \rightarrow p\ p\ e^-$	(CC)	1.44 MeV
(2)	$\nu_x\ d \rightarrow \nu_x\ p\ n$	(NC)	2.22 MeV
(3)	$\nu_x\ e^- \rightarrow \nu_x\ e^-$	(ES)	------

At these low energies, the deuteron charged-current (CC) reaction can proceed only with electron neutrinos. This reaction would be detected by the Cerenkov light produced by the electron. A measurement of the electron energy spectrum from the CC reaction directly gives the ν_e spectrum since the product electron, due to kinematics, carries away essentially all of the energy, minus the Q value, of the incident neutrino. A measurement of the electron angular distribution for the CC reaction gives the incident neutrino direction since the differential cross section has a well known forward/backward asymmetry. Thus, the CC reaction could be used to directly measure the ^8B electron neutrino flux, spectrum, and direction.

Table 1. Properties of the Sudbury Neutrino Observatory (SNO) Heavy Water Cerenkov Detector

DEPTH underground:	6.2 kmwe
COSMIC RAY rate:	100 /day
overall CAVITY size:	20 m cylinder
TOTAL D_2O mass:	1000 tonnes
SENSITIVE mass (including H_2O):	3300 tonnes
FIDUCIAL mass:	1000 tonnes
PHOTOELECTRONS per MeV:	7 p.e./MeV
ENERGY resolution (7 MeV):	17 %
TIME resolution (per PMT):	7.7 ns
SPATIAL resolution:	1 m
ANGULAR resolution (7 MeV electron):	35^o
water TEMPERATURE:	10^oC

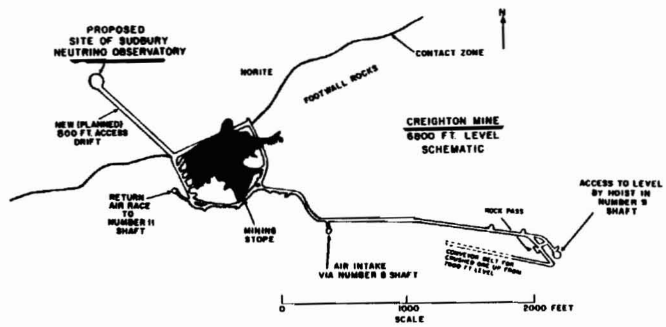

Fig. 3 Schematic of 6800 feet level in Creighton Mine

In this energy range, the deuteron neutral-current (NC) reaction cross sections are equal for arbitrary flavor neutrinos and anti-neutrinos. Thus, the NC reaction can be used to directly measure the total ^8B neutrino flux independent of neutrino flavor.[13] Detection of the NC reaction would occur via Cerenkov light produced by an electromagnetic cascade resulting from capture of the neutron on an appropriate target in the detector. The simplest approach makes use of neutron capture on the deuteron:

(4) $\qquad n\ d \rightarrow t\ \gamma$

to produce mono-energetic 6.25 MeV gammas. These would then be detected by their interactions in water, mostly Compton scattering, to produce electrons which then produce Cerenkov light.

Due to kinematics of the reaction, the cross section for neutrino-electron elastic scattering (ES) has a unique and distinctive sharp forward peak. This reaction would also be detected by the Cerenkov light produced by the electron. However, in application, the ES reaction is less useful because of the strong dependence of the ES cross section on neutrino flavor.[14,15] From standard electroweak theory[16,17,18] $\nu_e\ e^-$ scattering, which has contributions from both the weak charged- and neutral-current interactions, has a cross section about six times larger than $\nu_\mu\ e^-$ ($\nu_\tau\ e^-$) scattering, which has only a contribution from the weak neutral-current interaction. This complicates the interpretation of any observation. Further handicaps in applying the ES reaction come from both its smaller cross section and the sharing of energy by the outgoing electron with the outgoing neutrino. Assuming $\nu_e\ e^-$ scattering with the largest ES cross section, the event rate for ES in the heavy water detector is an order of magnitude smaller than the CC rate. The sharing of energy by the recoil electron with the outgoing neutrino results in a distribution of recoil electron energies given an incident mono-energetic neutrino. So, a measurement of this recoil electron spectrum gives an integral of the incident neutrino spectrum rather than directly the neutrino spectrum. Nevertheless, if the ^8B electron neutrino flux and spectrum can be determined accurately by the CC reaction, then the component of $\nu_e\ e^-$ in the total ES signal can be subtracted in order to search for a possible $\nu_\mu\ e^-$ ($\nu_\tau\ e^-$) signal.

Thus, it would have a sensitivity to the spectrum and direction of any ^8B originated electron neutrinos which may have oscillated into muon or tau neutrinos.

Given the potential to detect three reactions, the capability to identify and to separate individual events from each reaction, if possible, would be highly desirable. Before committing the use of heavy water, the initial fill of the SNO detector, for a complete system test, must be with H_2O. Thus, the H_2O provides an appropriate opportunity to study the ES reaction alone. However, the technique described above for detection of the NC reaction in pure D_2O interferes with the CC spectral measurement unless the neutron capture reaction (4) is suppressed by using an additive, e.g. ^{10}B, to provide an alternate neutron capture reaction. The measurement of the total ^8B flux via the NC reaction is accomplished by taking data both with pure D_2O and with ^{10}B loaded D_2O. Then, the rate difference gives the total ^8B flux independent of neutrino flavor.

Standard Solar Model Event Rates and Sensitivity

Assuming the standard solar model, which predicts a ^8B flux at the earth of 4×10^6 /cm^2 /sec, the number of events expected in the SNO detector after one year of operation, a kiloton-year (kT-yr), is shown in Table 2. Column 1 gives the reaction of interest while column 2 gives the total number of events expected for each reaction. The number of events observed, with the detection efficiency for each reaction included, is given in column 3. The detection efficiency for the CC reaction is high even with a 7 MeV detection threshold. The detection efficiency for the NC reaction is low because reaction (4), the neutron capture reaction on deuterons, has a small cross section as compared to neutron capture on free protons. Thus, even though the 6.25 MeV photon may be detected with high efficiency, assuming a 5 MeV detection threshold, only some 20% of the neutrons would be captured by deuterons. Of the remainder, 50% diffuse to the H_2O blanket and are captured in hydrogen, 25% are captured in residual hydrogen in the D_2O, and 5% are captured in oxygen. The use of an additive in heavy water with a large neutron capture cross section and good conversion to electromagnetic radiation, e.g. gadolinium, silver, salt, may be used to improve the NC detection efficiency from below 20% towards 100%. The detection efficiency for the ES reaction is low because of energy sharing by the outgoing neutrino with the outgoing electron, which then falls below the 7 MeV detector threshold. By operating the detector threshold near 5 MeV, the ES detection efficiency can be improved from about 20% towards 40%.

The last column in Table 2 gives, for each reaction, the ^8B neutrino flux sensitivity of the SNO detector at three standard deviations after one year of operation, one kT-yr. All estimated backgrounds for the CC and ES reactions, which total less than 2 events/day and are from external gamma-ray sources, have been included for this estimation. The backgrounds for the NC reaction, has both external and internal sources to be considered. The external background sources are at the same level as that for the CC and ES reactions. The internal sources have to be reduced by about a factor of ten from our present estimation in order for the NC experiment to be feasible.

With backgrounds for the NC reaction still to be overcome, nevertheless the feasibility of the CC and ES reactions for detecting ^8B solar neutrinos have been established, and the design capabilities of the proposed SNO detector has sensitivities far below the standard solar model prediction of 4×10^6 /cm^2 /sec.

Table 2. ^8B event rates with the standard solar model and flux sensitivity (one kT-yr)

Detected Reaction	No. Events	No. Events x Detector Efficiency	Flux Sensitivity (/cm^2 /sec)
ν_e d (CC)	9000	5474 *	4×10^4
ν_e d (NC)	4500	712 +	4×10^5 #
ν_e e (ES)	2400	516 *	2×10^5

* 7 MeV threshold
\+ assumes neutron capture by deuteron and a 5 MeV threshold for detecting the 6.25 MeV gamma ray.
\# see text for a discussion of backgrounds.

Radioactivity Background Measurements

Backgrounds for this experiment come from the cosmic rays, the underground mine environment, and the detector materials. We have attempted to minimize these backgrounds both by choice of detector location and detector materials. Measurements and simulations of the various types of backgrounds have indicated that for the CC and ES reactions the backgrounds will be under control. The NC requires stringent control of the U and Th contents, in particular in the acrylic, D_2O and H_2O. The levels required are such that it is necessary to improve the sensitivity of our present measurement techniques in order to demonstrate that these backgrounds will be under control.

Status of SNO Design Study

An engineering design study was initiated in order to begin to quantify in detail all the essential parameters for the SNO detector conceptual design given above. Other aspects of the conceptual design requiring additional studies have been or are being carried out. For example, an initial engineering design study, with full stress analysis, for the acrylic heavy water containment vessel is complete and concludes that construction of such a vessel is feasible. A 250 m access drift is presently being excavated by INCO at the 2073 m level in the Creighton mine in order to obtain core samples which will finalize the location of the cavity. The SNO final design will be fully supported by the results of calculations, measurements, by technical reports and by signed agreements.

Summary

Using the CC reaction, the SNO detector can measure the ^8B electron neutrino flux, spectrum and direction. Using the ES reactions, it would also have a sensitivity to the spectrum and direction of any ^8B originated electron neutrinos which may have oscillated into muon or tau neutrinos. If backgrounds internal to the detector can be reduced by removing U and Th, as we believe, then the SNO detector can also measure the total ^8B neutrino flux, irrespective of neutrino flavor.

An engineering design study has been commissioned to verify that a large cavity at 2073 m depth can be constructed, to determine that 1000 tons of D_2O can be handled realistically, to obtain detailed designs, and to produce construction cost estimates. A program to determine methods of further reducing the internal background for the neutral current experiment continues and recent progress in this direction has been very encouraging.

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